Modelling of Electron Cyclotron Resonance Heating for COMPASS-U

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FTTF workshop
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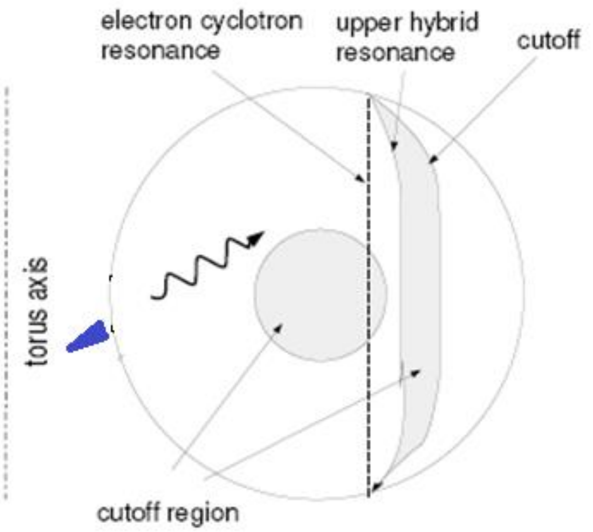
Outline

- Motivation
- Electron Cyclotron Wave Physics
- ECRH for COMPASS-U
- SPECE code – Ray-Tracing
- Preliminary Results
- Summary

COMPASS-U will be equipped with an NBI heating system.
An additional ECRH heating is planned on the tokamak.



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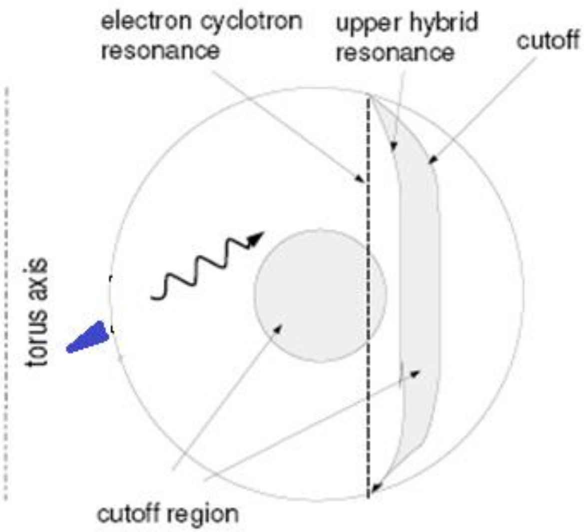

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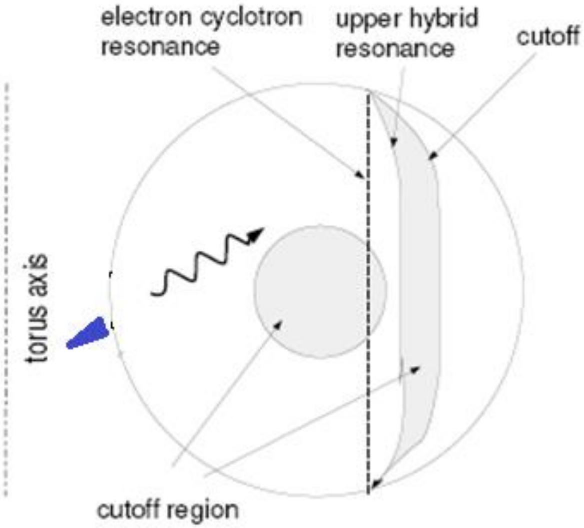

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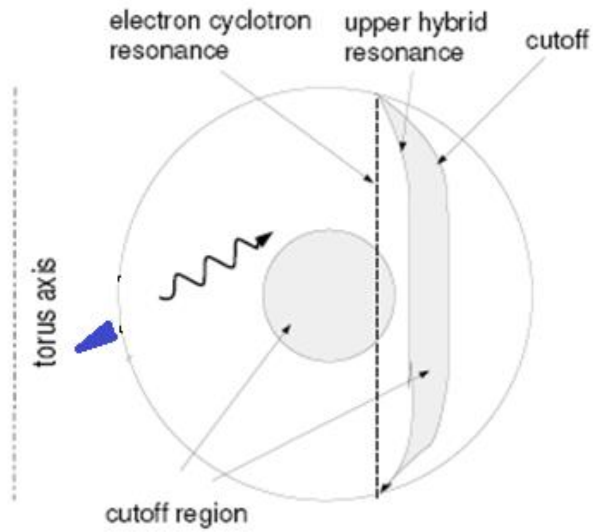

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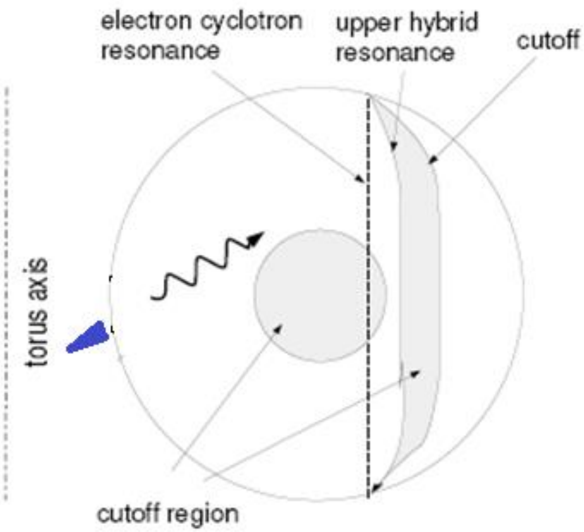

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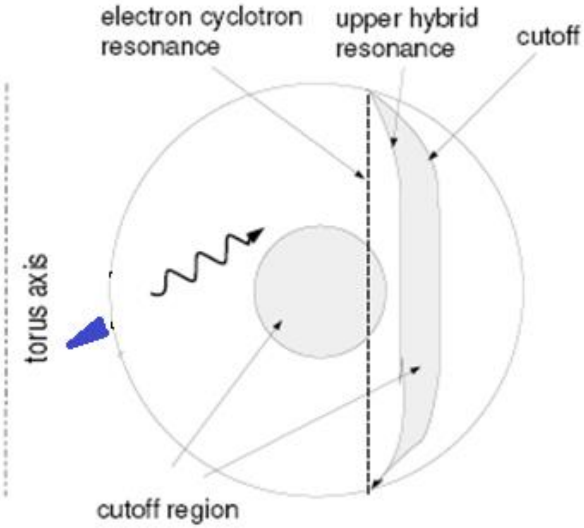

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- Current Drive (ECCD) – profile tailoring

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Appleton-Hartree formula

$$N^2 = 1 - \frac{2X(1-X)}{2(1-X) - Y^2 \sin^2\theta \pm \left[Y^4 \sin^4\theta + 4Y^2 (1-X)^2 \cos^2\theta\right]^{1/2}}$$

$X = (\omega_p/\omega)^2$ a $Y = \omega_c/\omega$

Perpendicular propagation

$$\text{Plasma cutoff} \quad \omega = \omega_{\mathrm{O}} = \omega_{pe},$$

$$\text{Right}-\text{hand cutoff} \quad \omega = \omega_{\mathrm{R}} = \left(\frac{\omega_{\mathrm{ce}}^2}{4} + \omega_{\mathrm{pe}}^2\right)^{1/2} + \frac{\omega_{\mathrm{ce}}}{2},$$

$$\text{Left}-\text{hand cutoff} \quad \omega = \omega_{\mathrm{L}} = \left(\frac{\omega_{\mathrm{ce}}^2}{4} + \omega_{\mathrm{pe}}^2\right)^{1/2} - \frac{\omega_{\mathrm{ce}}}{2}.$$

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Hot plasma – Kinetic theory

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\frac{\partial f}{\partial \mathbf{r}} - e\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}\right)\cdot\frac{\partial f}{\partial \mathbf{p}} = 0$$

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Resonance condition

$$\omega = \frac{n \cdot \omega_c(B, v)}{1 - \beta_{\parallel} N \cos(\theta)} + k_{\parallel} v_{\parallel}, \quad \omega_c(B, v) = \frac{eB}{m_e(v)}$$

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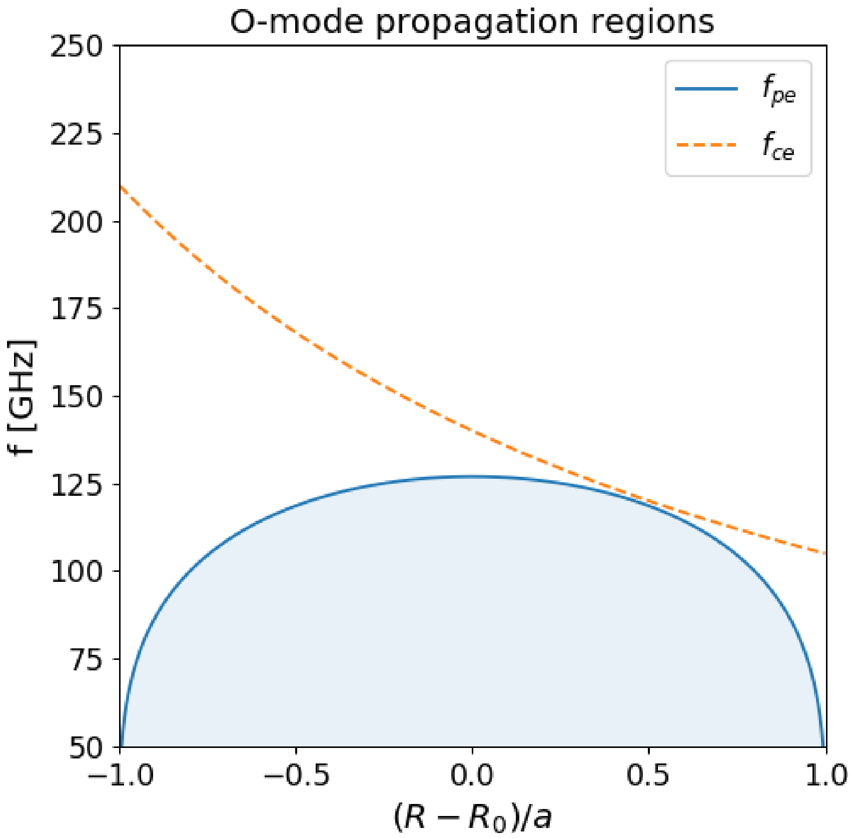
***n*-th harmonic** **Doppler shift** **Relativistic mass**

COMPASS-U


O-mode propagation regions
250
225
200
175
150
125
100
75
50
f [GHz]
−1.0
−0.5
0.0
0.5
1.0
(R − R0)/a
fpe
fce

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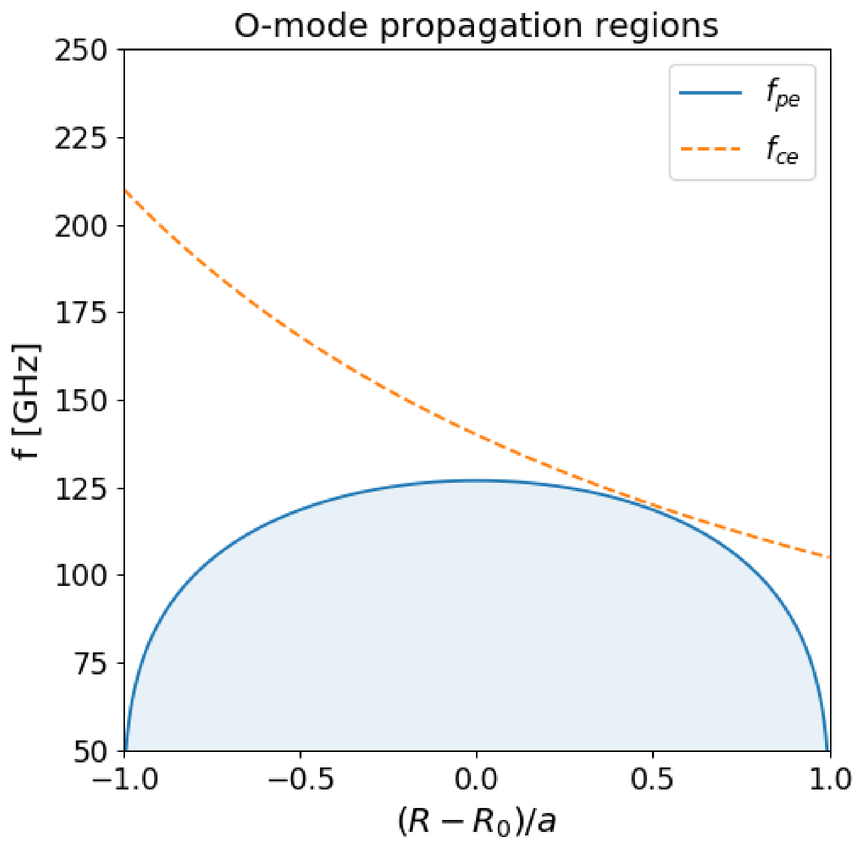
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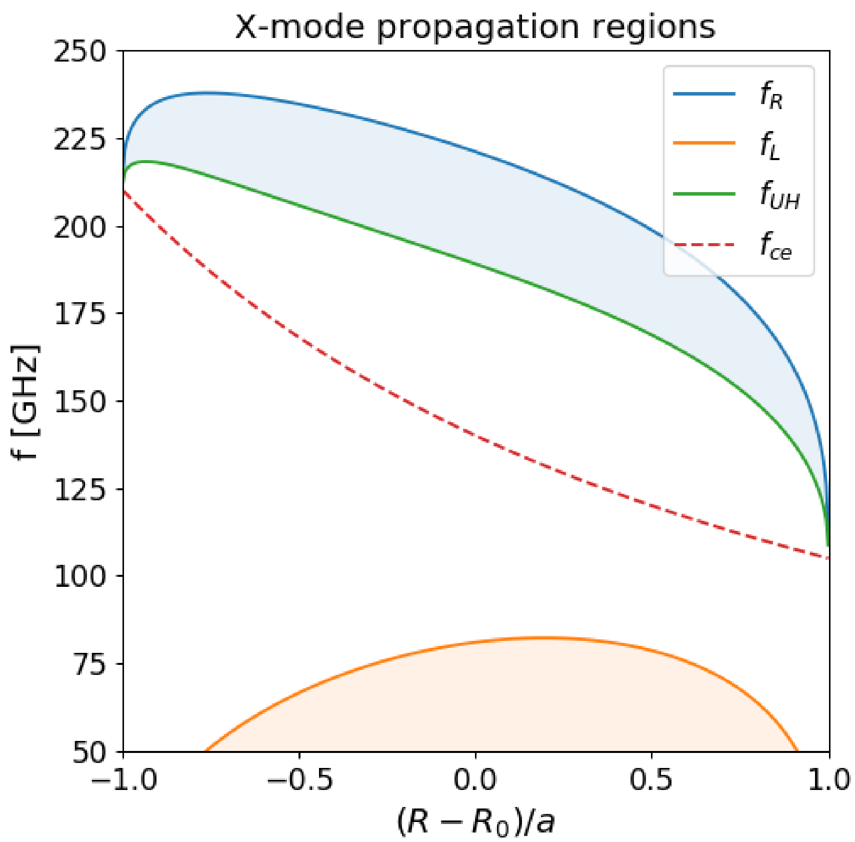
X-mode propagation regions
f_R
f_L
f_{UH}
f_{ce}
f [GHz]
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175
150
125
100
75
50
−1.0
−0.5
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ECRH for COMPASS-U

- **COMPASS-U**: DEMO relevant research (R_0 = 0.84 m, a = 0.28 m)
  B_T: 5 T, I_p: 2 MA, discharge length 1-5 s, **n_e: ~ 10^{20} m^{-3}**
  P_{NBI} = 4-5 MW, **P_{ECRH} = 4 MW**

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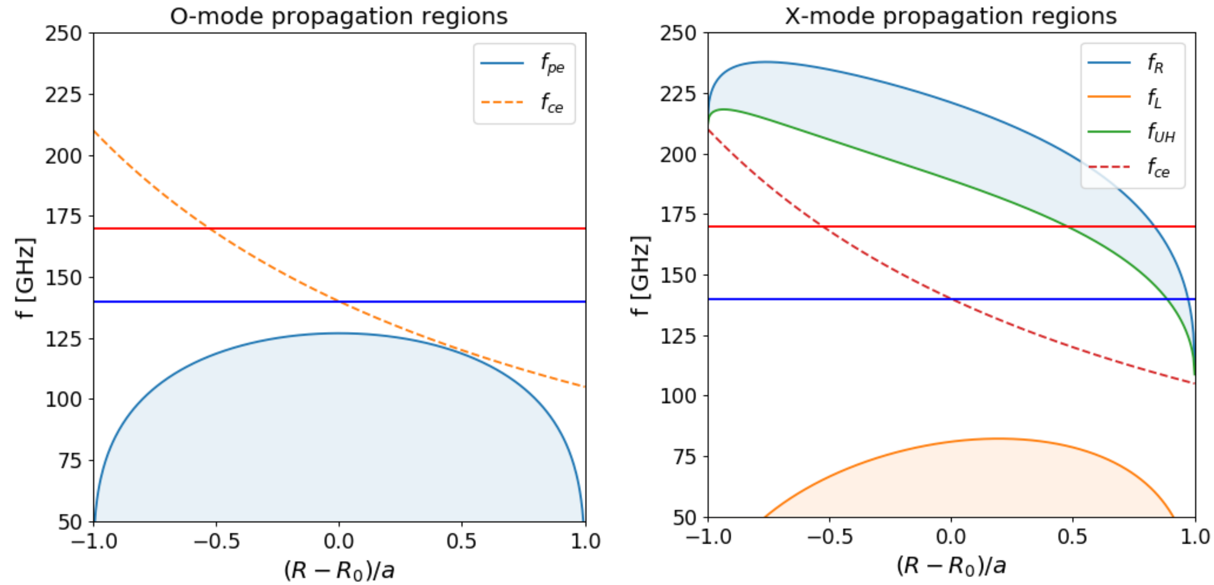
- O-mode: **cutoff density ≈ 2.5·10^{20} m^{-3}** for **140 GHz**
  X-mode: core achievable from the HFS

Reminder:



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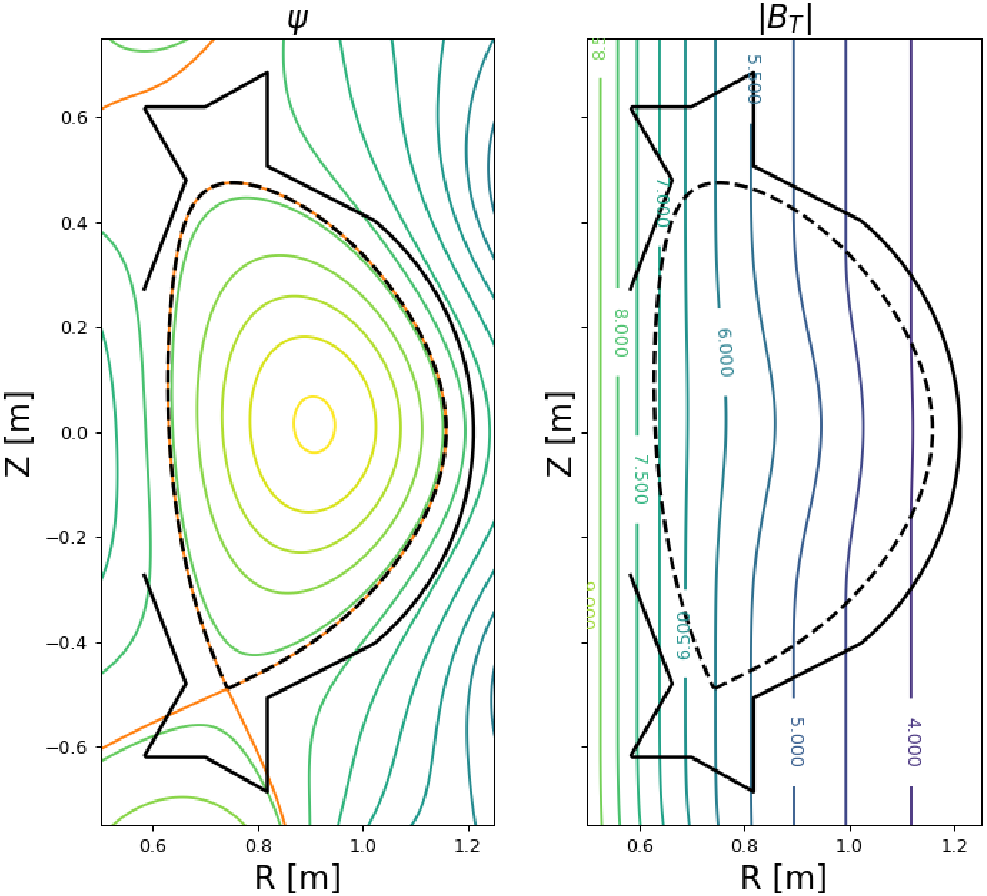
- **Higher harmonic heating not possible** with current gyrotron technology (250 GHz gyrotron **GYCOM** in testing phase)
- **1st harmonic X-mode** is optically thin thus **not suitable** for the ECRH
- HFS launcher or mirror technically difficult

SPECE code[4]



Baseline 5T scenario equilibrium

Credit: PLEQUE – L. Kripner

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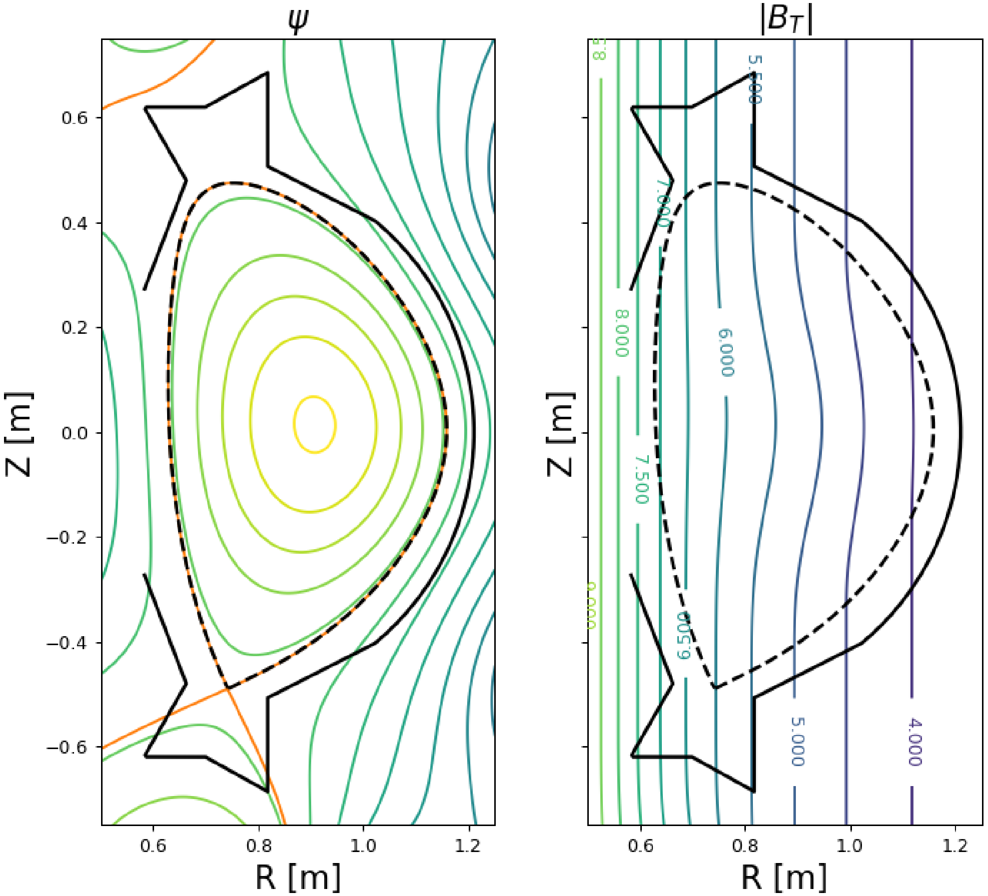

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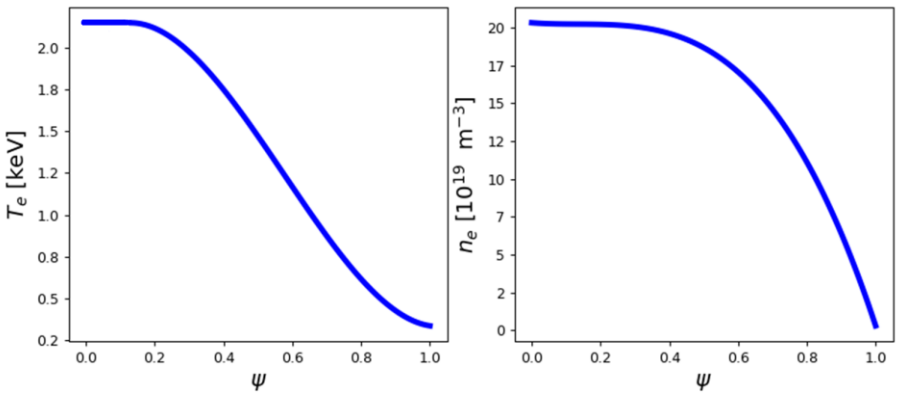
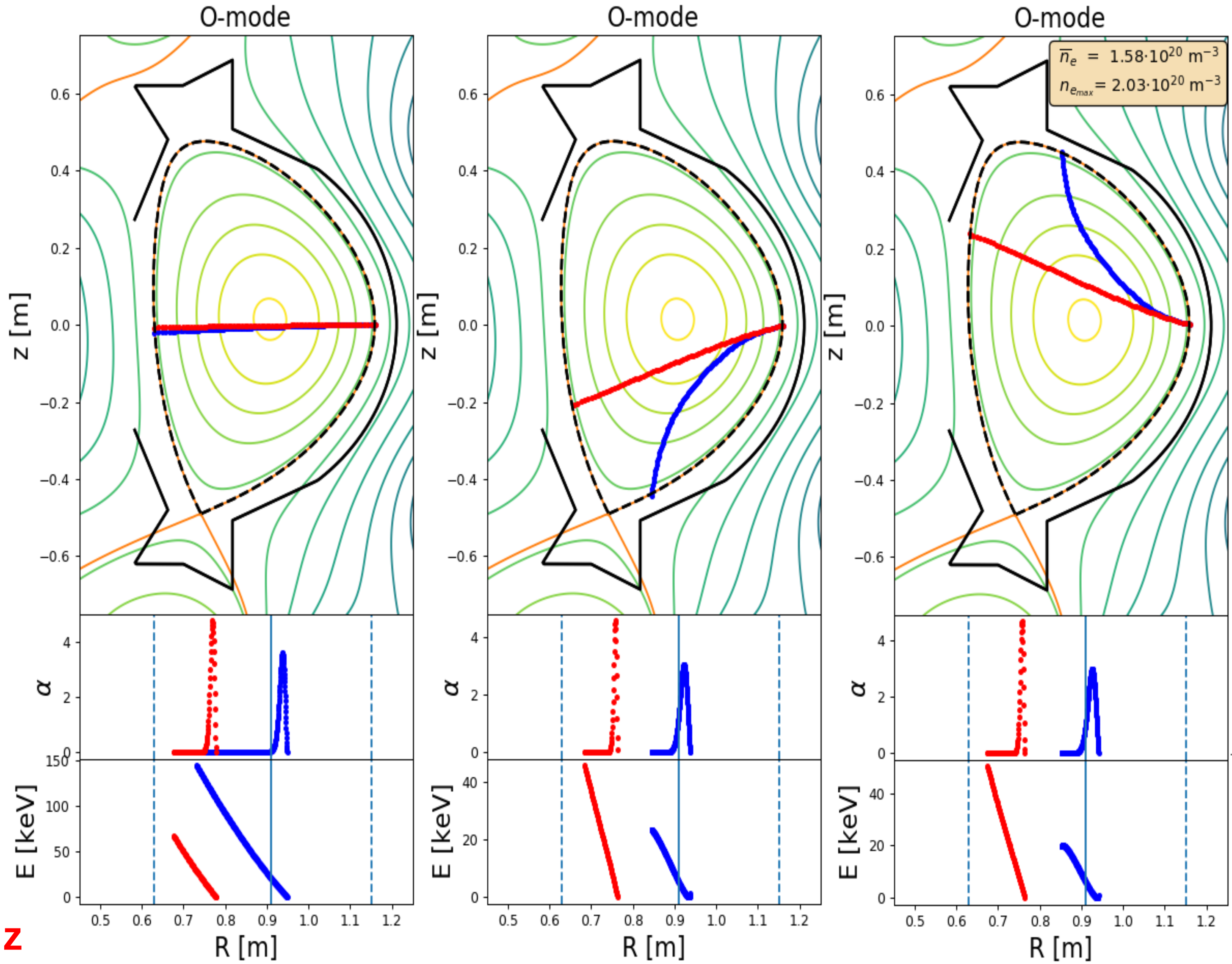
Temperature and density profiles



Preliminary Results

Core density below cutoff condition



140 GHz **170 GHz**

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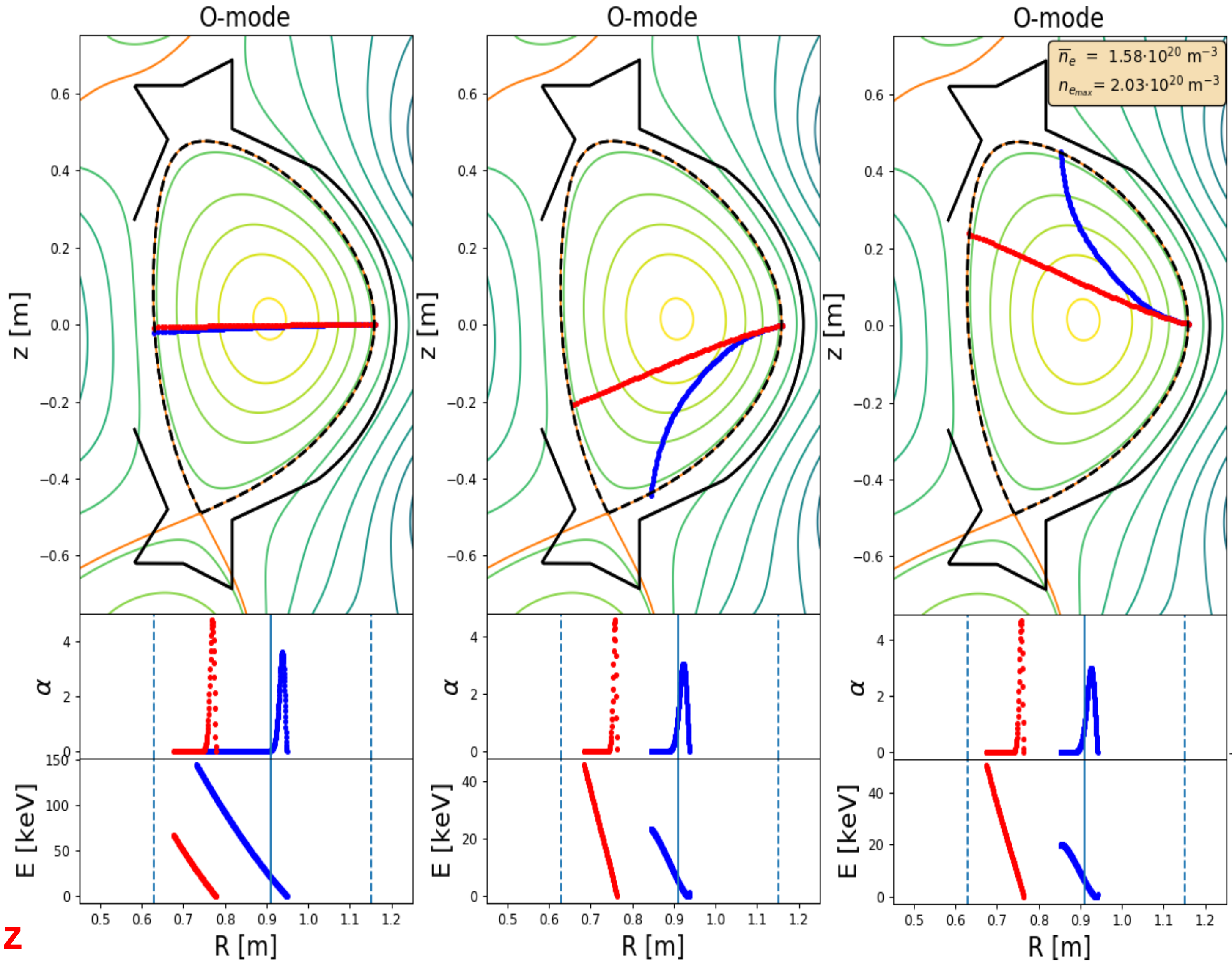
Everything just fine!

Perpendicular propagation poloidal angle ± 14°



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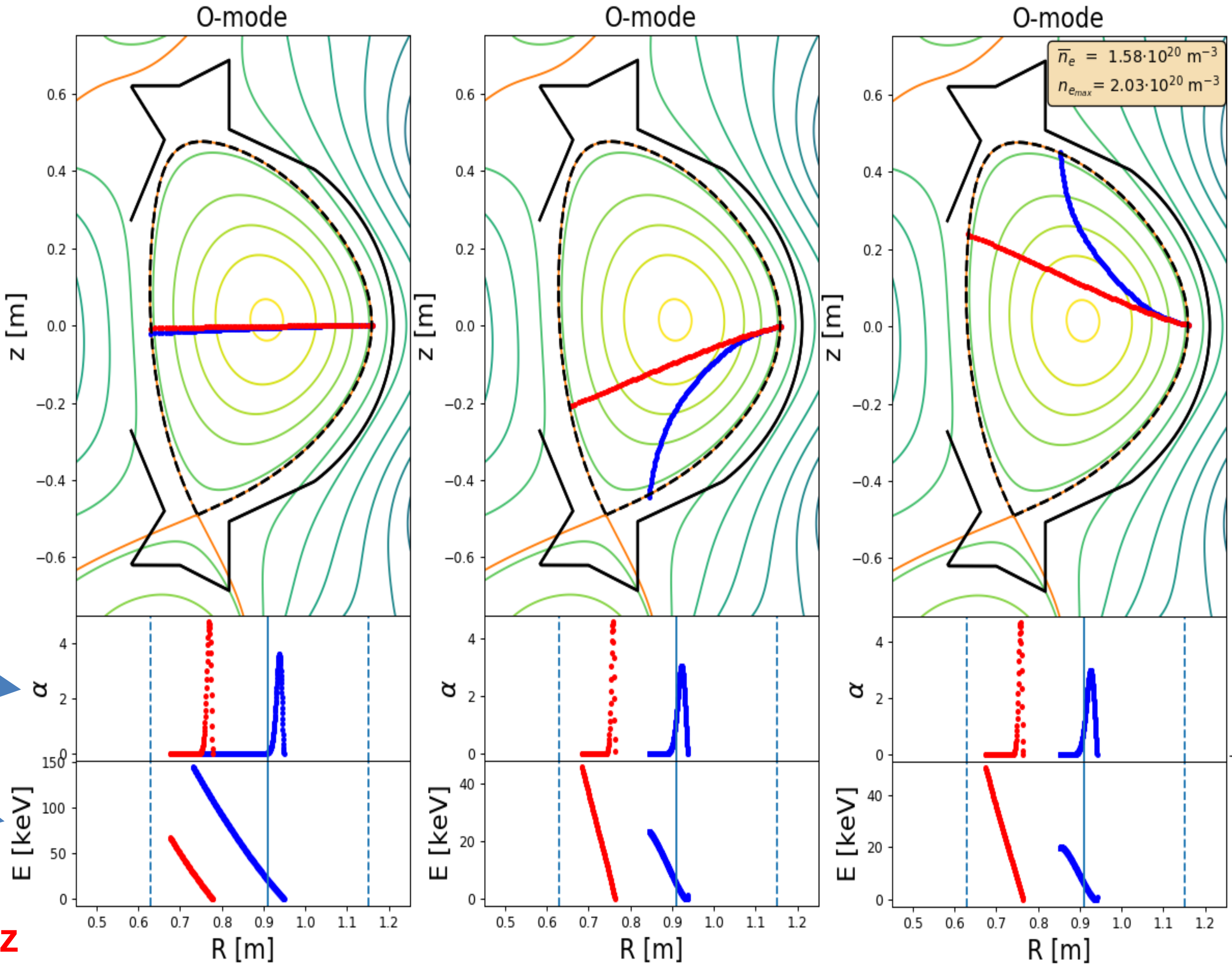
absorption coef.

kinetic energy of resonant electrons



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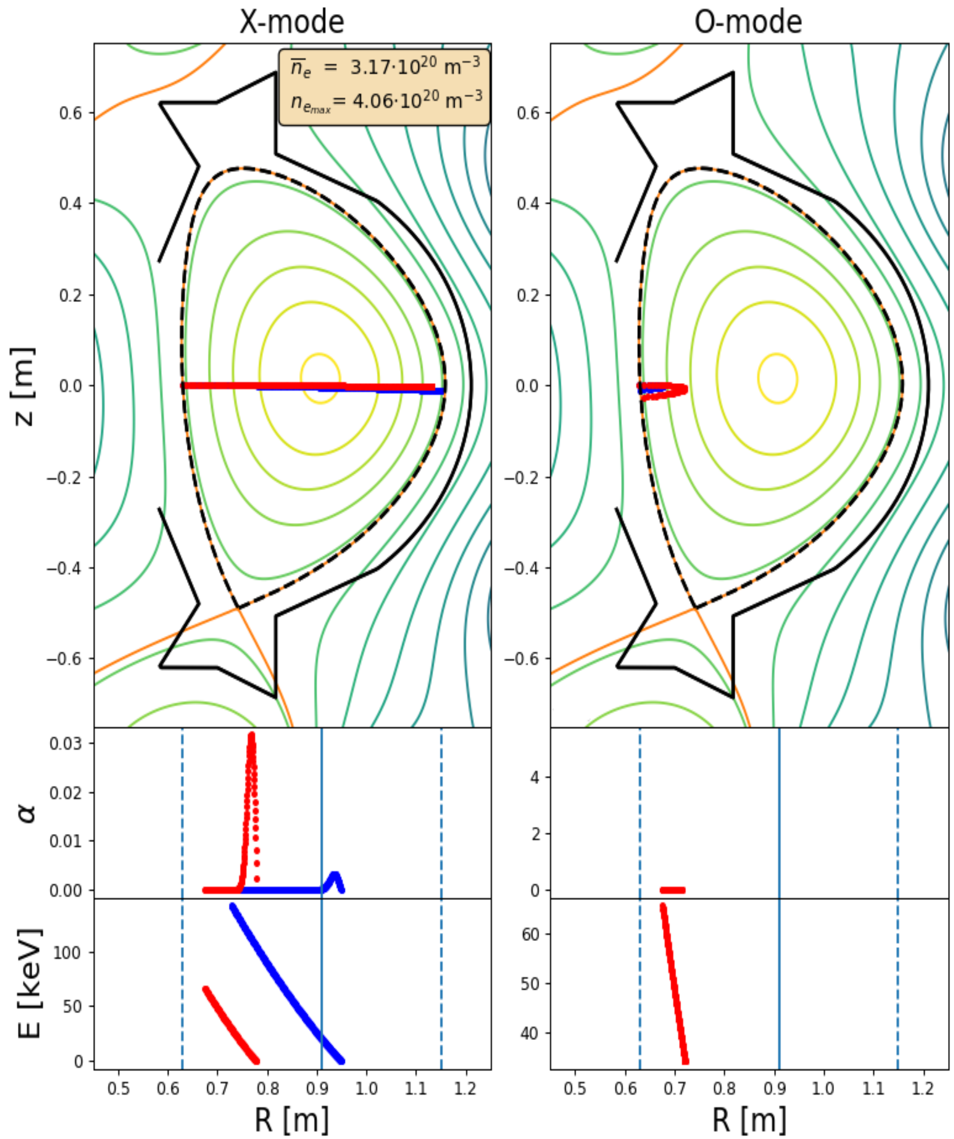

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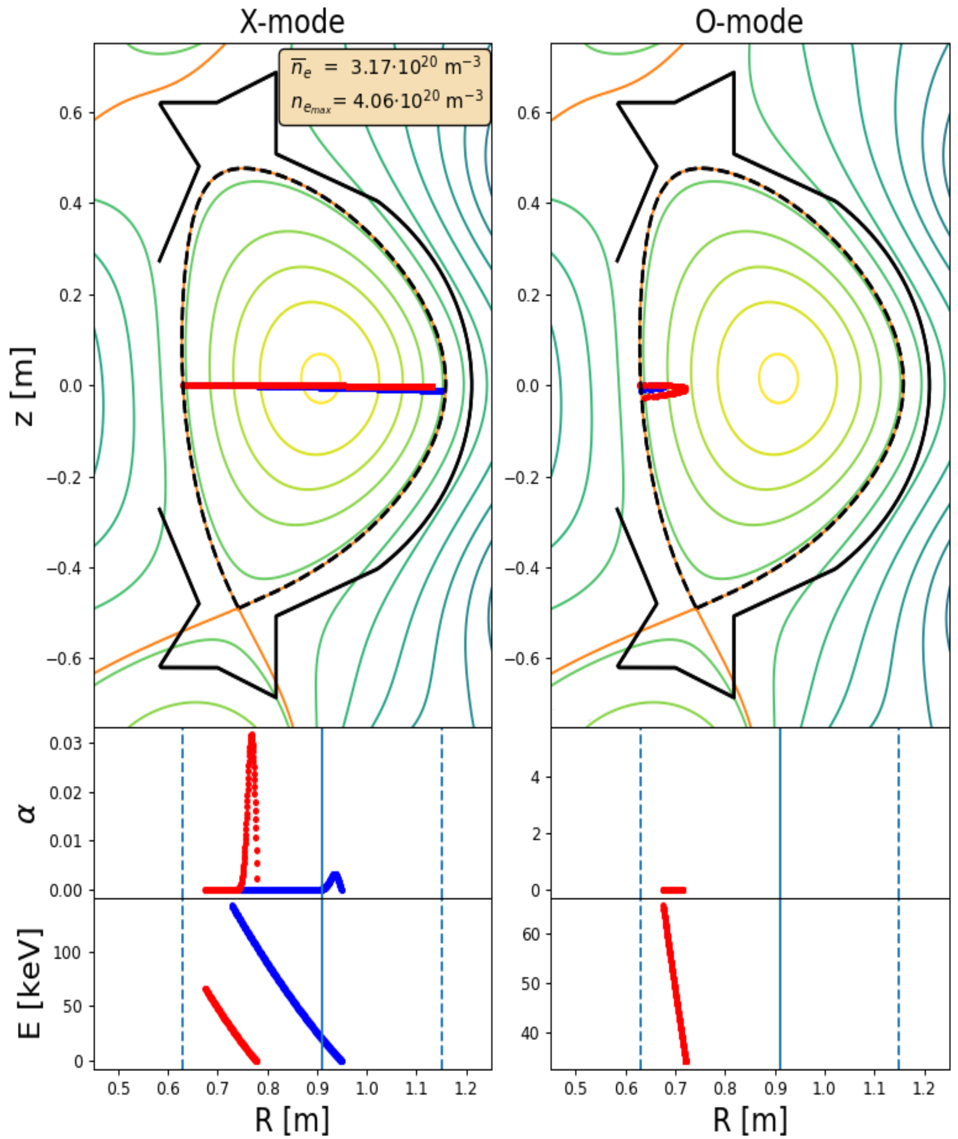

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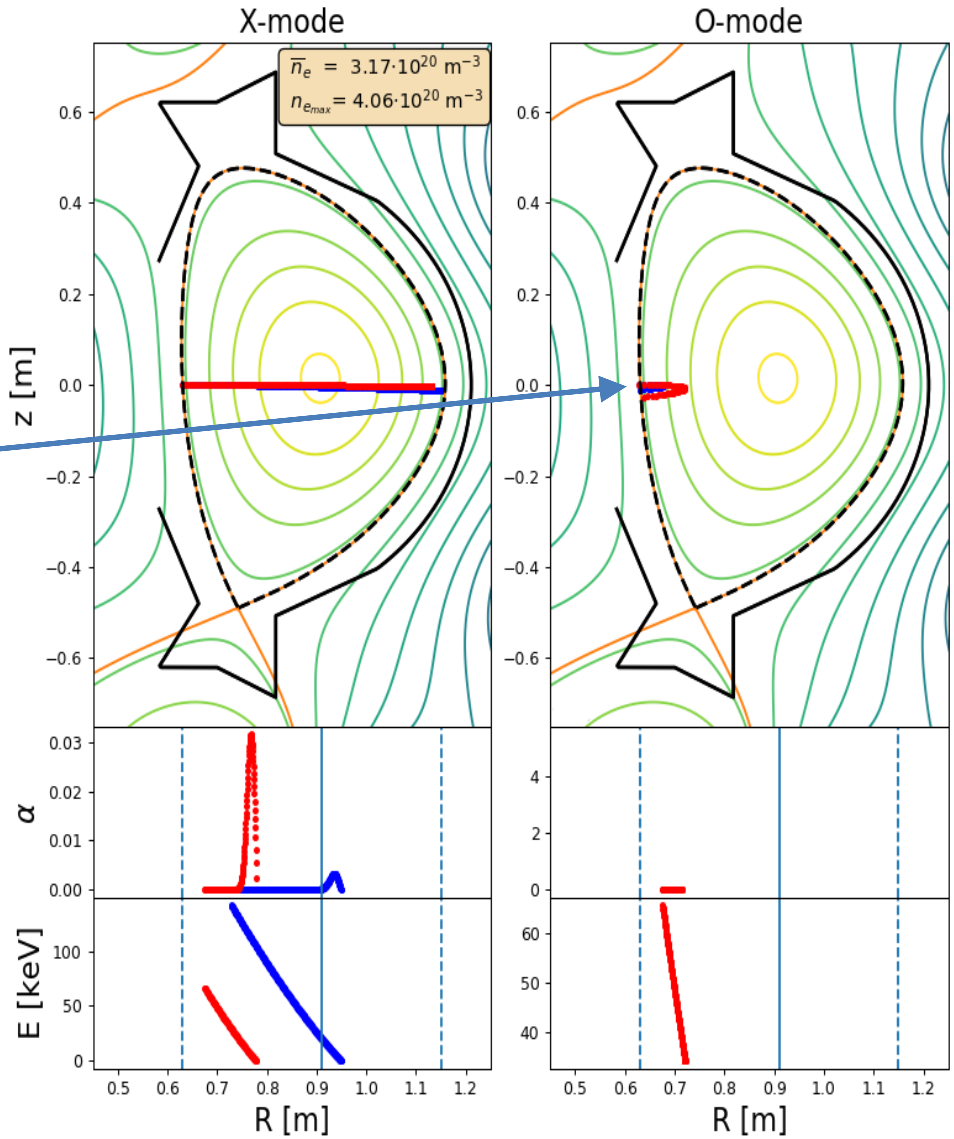

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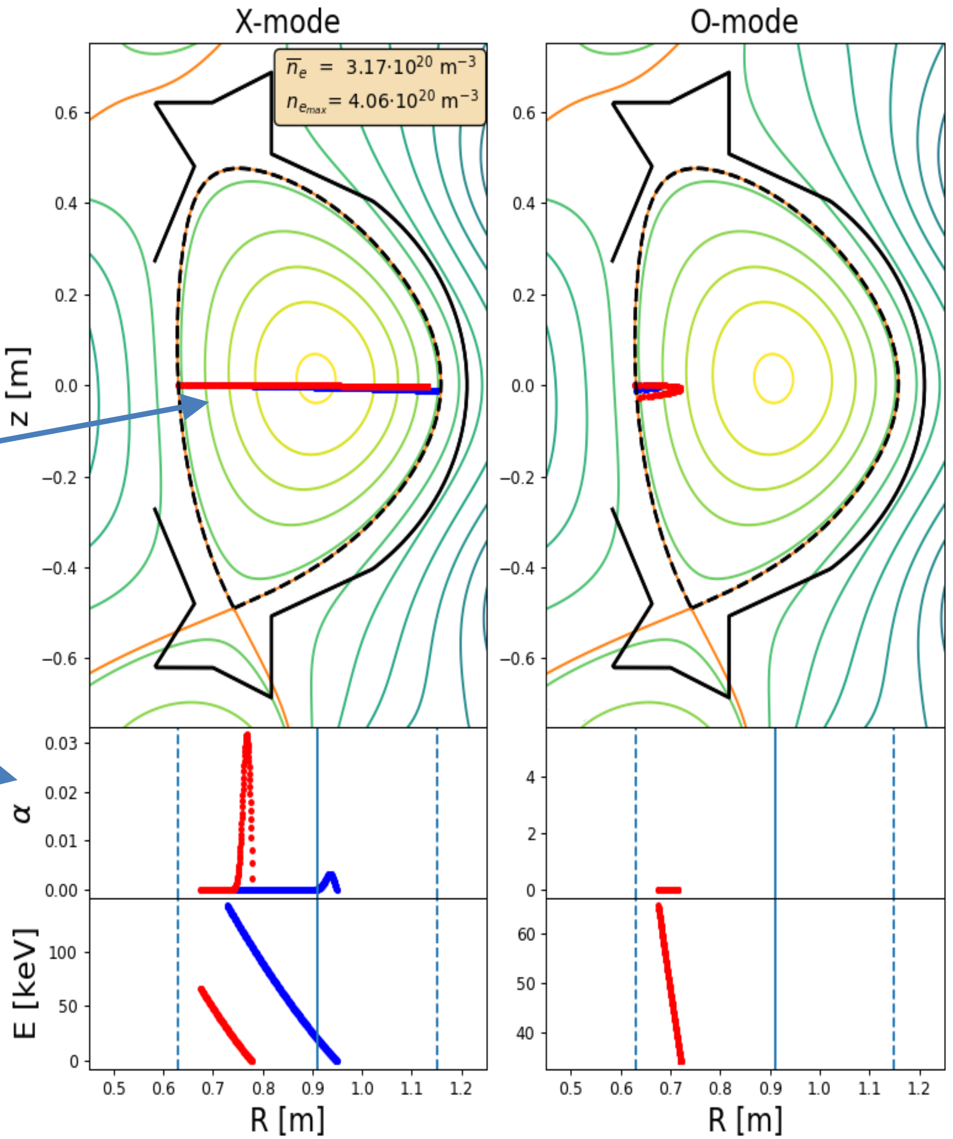
X-mode → from HFS but low ***α***
100x lower than O-mode



140 GHz 170 GHz

Preliminary results

Greenwald density: $n_G = \frac{I_p}{\pi a^2}$

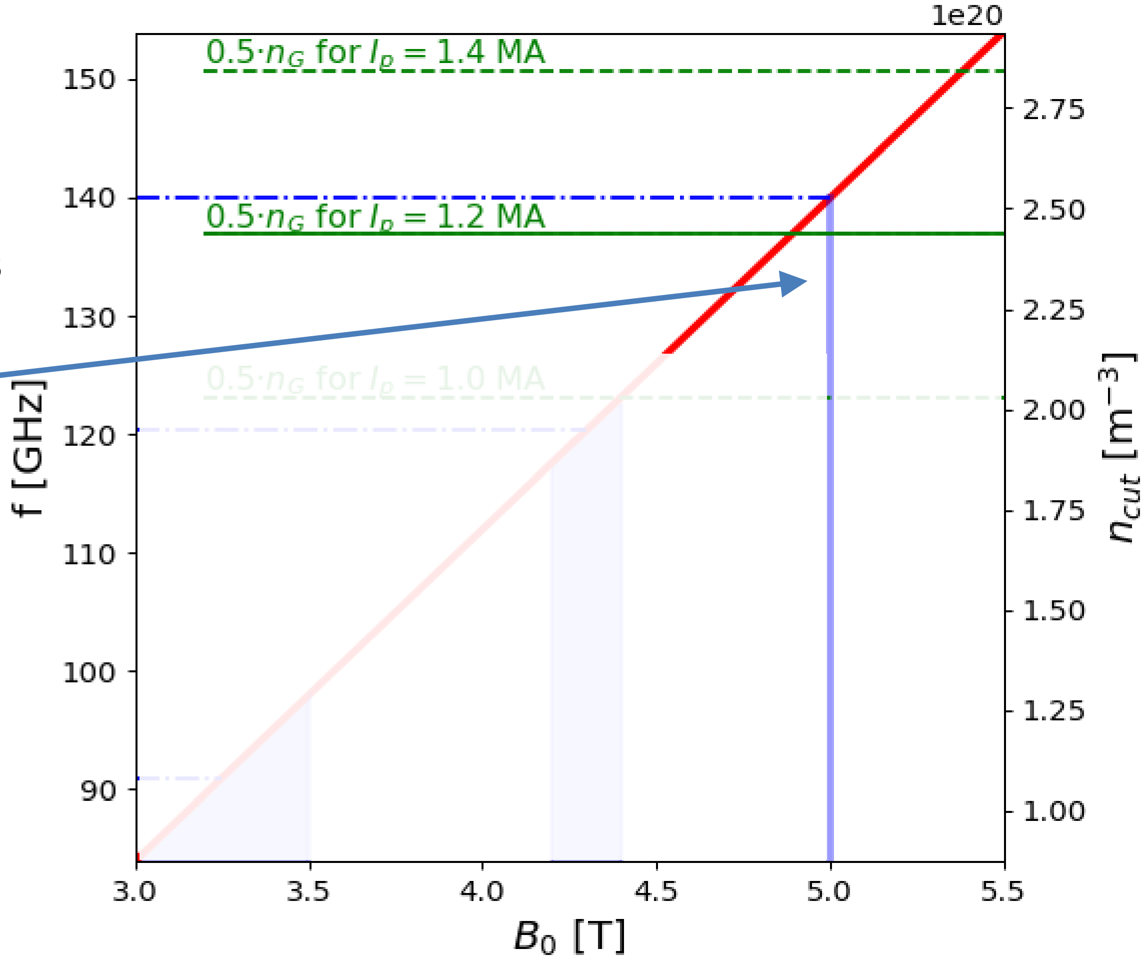
Natural H-mode density ≈ 0.5·n_G

note: not maximum density!
not for 300°C hot wall

5 T → 140 Ghz
n_{cut} = **2.5·10^{20} m^{-3}**

Only H-mode discharges with $I_p \leq$ 1.2 MA

COMPASS-U: 2 MA desired



Proposal: ECRH for the High B-field (5 T) Dischages

Frequency: **140 – 150 GHz**

O-mode cutoff: **2.5 - 2.8**$\cdot$**10^{20} m^{-3}**

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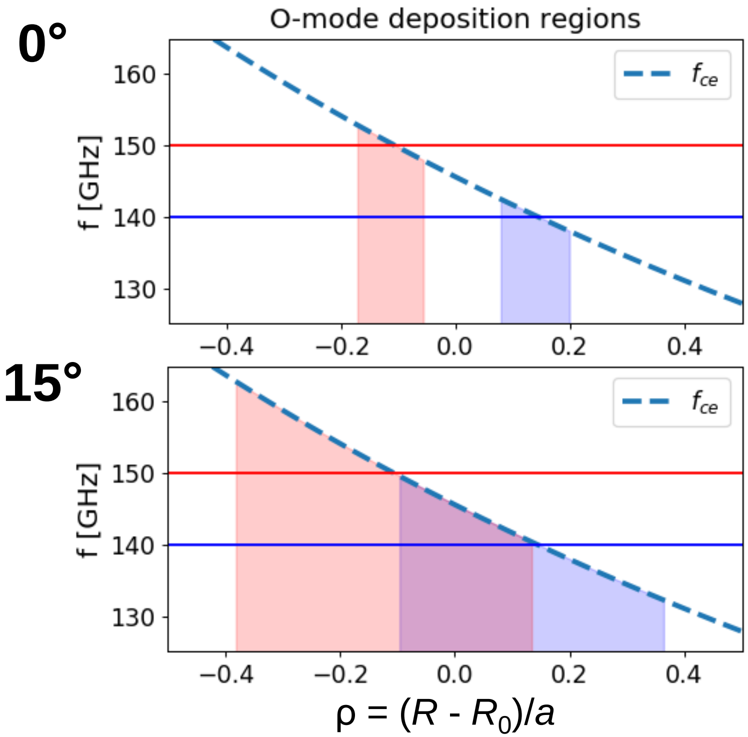

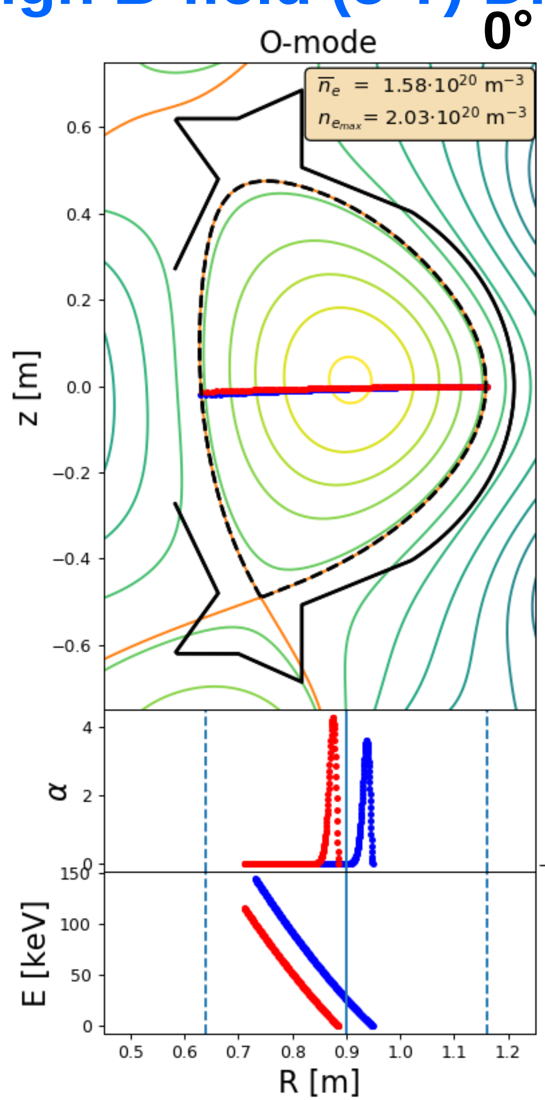

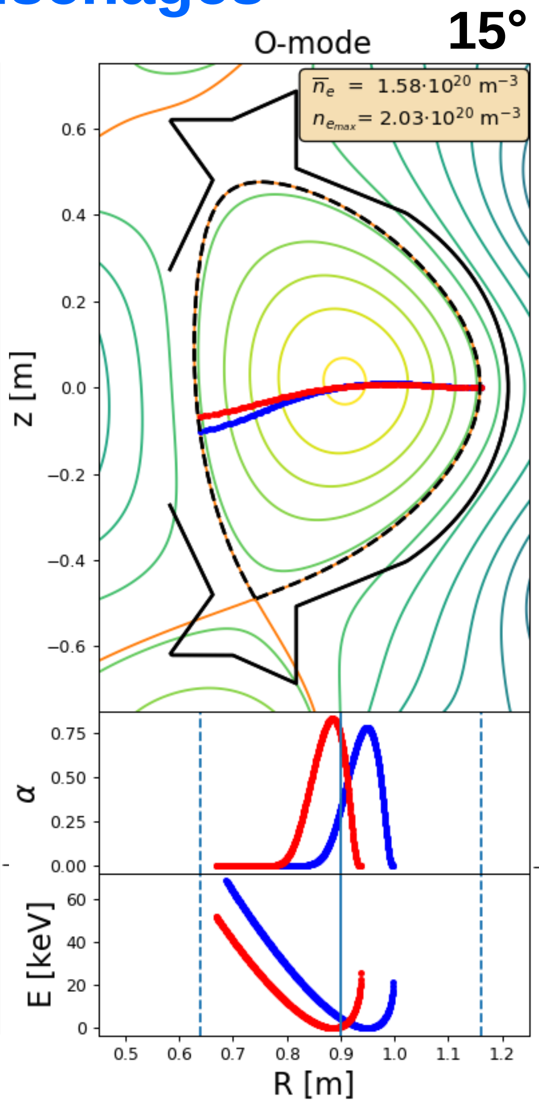

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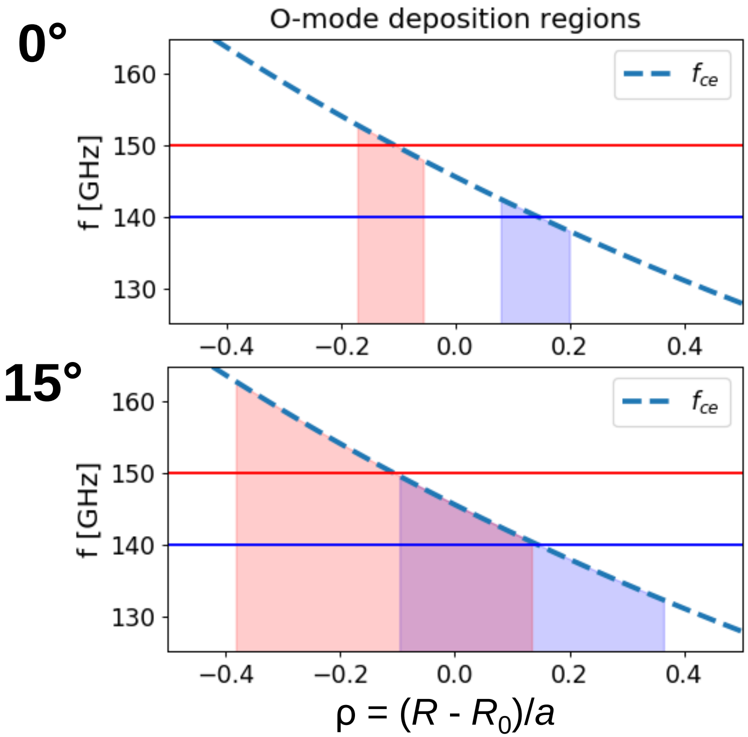

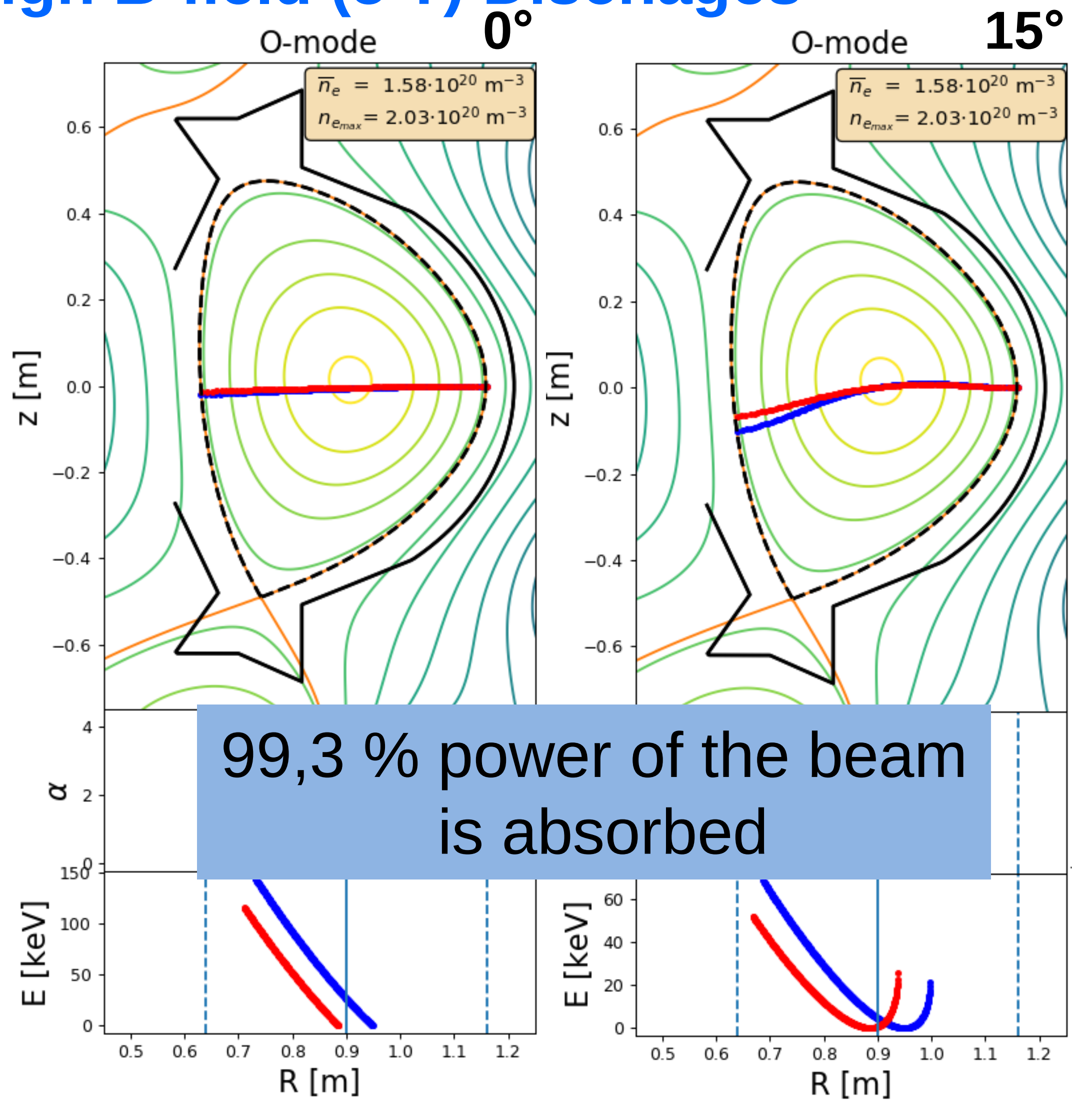

99,3 % power of the beam is absorbed

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- Natural H-mode density in preffered discharge scenarios is much higher than the cutoff condition. ECRH will not be usefull in later phases of these discharges.
- It is necessary to model the behaviour of plasma in H-mode at COMPASS-U.
- To avoid these restrictions, we should cooperate with the DEMO gyrotron developement group in Russia.

Reference

[1] MAZZUCATO, E., *Electromagnetic Waves for Thermonuclear Fusion Research*. Singapore: World Scientific, 2014. ISBN 9789814571807

[2] STIX, T. H., *Waves in Plasmas*. New York: American Institute of Physics, 1992.

[3] BORNATICI, M., et al., Electron cyclotron emission and absorption in fusion plasmas. *Nuclear Fusion*. 1983, vyd. 23, c. 9, s. 1153.

[4] FARINA, D., et al., SPECE: A code for electron cyclotron emission in tokamaks. In *AIP Conference Proceedings*, volume 988, pages 128–131,2008.